THE SOLID STATE ENERGY CONVERSION ALLIANCE (SECA)- A U. S. DEPARTMENT OF ENERGY INITIATIVE TO PROMOTE THE DEVELOPMENT OF MASS CUSTOMIZED SOLID OXIDE FUEL CELLS FOR LOW-COST POWER

W. A. Surdoval
U. S. Department of Energy, National Energy Technology Laboratory
626 Cochrans Mill Road, Pittsburgh, PA 15236, USA

S. C. Singhal and G. L. McVay
Pacific Northwest National Laboratory
902 Battelle Boulevard, Richland, WA 99352

ABSTRACT

The Solid State Energy Conversion Alliance (SECA) was initiated in the fall of 1999 to encourage the development of environmentally friendly solid oxide fuel cell (SOFC) modules for use with commonly available fossil fuels at low cost. In order to quickly achieve the necessary manufacturing volume to reduce costs to commercially acceptable levels it was decided that a mass customized base module applicable to stationary, mobile, and corollary military needs was required. A 3–10kW base module was selected due to judgements on the upper size limit of high-power density ceramic based cells, a lower limit of economic self-sustainability, and considerations that indicated this size range had broad applicability in the three targeted sectors. Larger systems would consist of multiples of this base module.

Substantial independent research and development work has been in progress for many years on the various components of solid oxide fuel cells. The U. S. Department of Energy (DOE) will provide support to encourage the formation of Industrial Teams that have the necessary components to develop, design, and manufacture the complete module and establish markets in as many of three targeted sectors as possible. Since it is not clear which solid oxide fuel cell technology has the best chance for success, multiple independent teams will be funded. A second component of the SECA Program will be the Core Technology Program that will fund independent research and development work in close support of the Industrial Teams.

The U. S. DOE's Strategic Center for Natural Gas, part of the National Energy Technology Laboratory, and the Pacific Northwest National Laboratory will lead the Alliance. Initial Industrial Team selections will be made in April of 2001.

GENESIS

The Solid State Energy Conversion Alliance was initiated to overcome the historical problem of the chicken or the egg in the fuel cell business; not enough units are sold to bring the price down and the price is too high to sell a large number of units. The combined residential, auxiliary power, and corollary military applications represent a substantial market and a basis for large-scale production if a common module were developed that could be applied with a minimal number of custom features to all of these market segments simultaneously.

Up to this time high temperature fuel cell systems have largely been developed for relatively specific niche applications with robust system design outweighing cost considerations. This approach has resulted in successful demonstration of the technology and application of a limited number of systems in the targeted niche applications. It provides the basis for moving into this next phase of development.

The United States Department of Energy is chartered to improve energy efficiency, ensure reliability of the energy supply, promote clean energy technologies, expand energy choices, and cooperate internationally on energy issues. The fuel cell has potential to address all of these goals if the technology is developed sufficiently for widespread use as a commodity producer of electricity. The DOE's Office of Fossil Energy has selected the solid oxide fuel cell, as its next target for fuel cell development due to its many advantages relative to these goals in both the near and longer term. The solid oxide fuel cell has significant short-term advantages due to its easy ability to operate well with existing fossil fuels as a result of its relatively high temperature of operation. If the longer-term energy picture evolves into a hydrogen economy the solid oxide fuel cell serves as an excellent transition technology since the solid oxide fuel cell performance can be perfected on fossil fuels while even better performance is obtainable with hydrogen from renewable energy sources.

WHY A NEW SOLID STATE FUEL CELL TECHNOLOGY?

Breakthroughs in solid oxide fuel cell technology in ceramic materials, design, and manufacturing indicate substantially enhanced power densities are possible, comparable to polymer electrolyte membrane (PEM) fuel cells, which enables the development of small compact units that can be commercialized in multiple applications utilizing a common set of components, i.e. mass customization. Although comparable to the PEM in power density, the SOFC has other advantages due to its high temperature of operation and solid state construction, in particular when the flexible use of commodity fossil fuels is an objective.

In addition, due to its high temperature of operation, the solid oxide fuel cell can be used in co-generation applications to produce hot water or steam and can be efficiently coupled with turbines, which further enhances the range of applications. At the same time solid and gaseous pollutants are negligible, enabling the SOFC's use in the strictest regulatory environments. Greenhouse gas emissions are also reduced due to the SOFC's inherently high efficiency without the need for potentially expensive remediation.

The other driver is cost. Although some of the materials used in an SOFC are relatively expensive compared to more common materials like iron or plastics, the cost is much less than that of the noble metals employed in lower temperature fuel cells. In addition, although some of the materials, such as lanthanum and yttrium, employed in SOFCs are currently expensive they are also abundant. The wholesale cost of the rare earth compounds may decrease with increasing demand. Noble metals such as platinum would most likely respond in the opposite fashion to a substantial increase in demand with their more fixed reserves. However, cost of the SOFC is heavily dependent on the design and an unnecessary millimeter can make a real difference in that cost. Cost effective manufacturing is also heavily dependent on design in the same sense. It should be possible to manufacture SOFCs using very simple and cost-effective manufacturing techniques such as tape casting, tape calendering, and screen printing. The design work must consider manufacturing at all stages.

A goal of the Solid State Energy Conversion Alliance is to provide the opportunity for Industry to start with a clean page in the development of a new generation of SOFCs. SECA will simultaneously take advantage of all of these attributes and provide a focused program to take advantage of the many years of research and development that has taken place via individual and not always coordinated efforts over the past several decades.

SECA STRUCTURE

The U.S. DOE considers SECA to be a pilot program. The structure (Fig. 1) is based on Government led integration of the Industrial Teams and the Core Technology

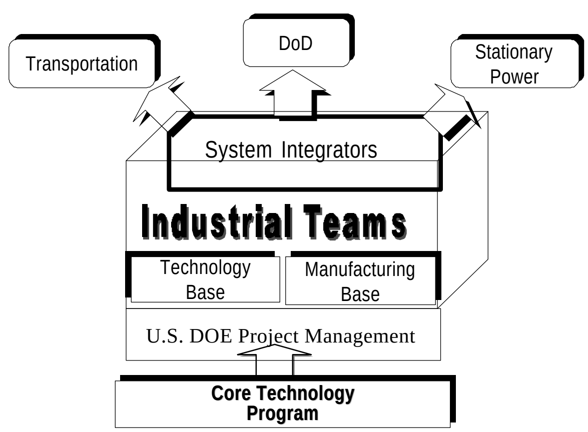

Fig. 1. The Solid State Energy Conversion Alliance Structure

Program. The Industrial Teams will have all the necessary components to immediately commercialize the SOFC product(s) within a short period of time after the product has been shown to have commercial applications. This means the Industrial Teams must not only have all the technical components but also have Team members with immediate access to the targeted markets. The targeted markets must be sufficiently large at the outset so the SECA cost goals can be met in a short period of time.

The Core Technology Program provides the focused applied research and development component of SECA, consisting of universities, industries, and national laboratories. The Core Technology Program participants will perform work subject to what is termed an "exceptional circumstance" to the Bayh-Dole Act (more on this later). This exceptional circumstance determination is the cornerstone of SECA and is what makes the program a true Alliance.

Another important aspect of the Program is that DOE will actively perform the task of integrating the Industrial Teams and the Core Technology Program. Past programs have been relatively vertical in nature with almost 100% of the funding directed at an industrial entity typically entailing little use of the research and development capabilities of universities, national laboratories and other research and development organizations. In the SECA Program, approximately 60% of the funding will be used to fund the Industrial Teams with the remainder of the funding directed at the Core Technology Program. DOE considers this funding split and the exceptional circumstance to the Bayh-Dole Act essential to solving the tougher technology issues faster without redundancy of effort while also ensuring the SECA Alliance members benefit expeditiously.

The Industrial Teams and Core Technology Program participants will be selected through competitive competition. A solicitation for selection of two to three Industrial Teams will close on January 24, 2001 with selection announcement occurring at the end of April. There will be two more proposal and selection opportunities in January 2002 and 2003. This will accommodate additional government sponsors and any additional funds. Having multiple Industrial Teams at the outset ensures that several different approaches are seriously developed until at least one approach proves commercially viable. Table I identifies the minimum requirements that the Industrial Teams are required to meet at the end of each phase in approximately 2005, 2008, and 2011 respectively.

A limited amount of work has started in the SECA Core Technology Program in the following areas:

- Multi-Layer Ceramic Manufacturing: develop multi-layer manufacturing techniques for application to SOFC's utilizing semi-conductor technology when possible.

- SOFC Materials Research: research on cathode and electrolyte materials to improve performance and lower operating temperature.

- National Laboratory applied research and development on critical SOFC issues.

Table I. SECA Industrial Team Minimum Requirements

	PHASE I	PHASE II	PHASE III
POWER RATING (NET)	3kW - 10 kW	3kW - 10 kW	3kW - 10 kW
COST	$800/kW	$600/kW	$400/kW
EFFICIENCY (AC or DC/LHV)	Mobile – 25 to 45%	Mobile – 30 to 50%	Mobile – 30 to 50%
	Stationary – 35 to 55%	Stationary – 40 to 60%	Stationary – 40 to 60%
STEADY STATE TEST @ NORMAL OPERATING CONDITIONS	1500 hours	1500 hours	1500 hours
	80% availability	85% availability	95% availability
	ΔPower ≤ 2% degradation/500 hours at a constant stack voltage.	ΔPower ≤ 1% degradation/500 hours at a constant stack voltage.	ΔPower ≤ 0.1% degradation/500 hours at a constant stack voltage.
TRANSIENT TEST	10 cycles	50 cycles	100 cycles
	ΔPower ≤ 1% degradation after 10 cycles at a constant stack voltage.	ΔPower ≤ 0.5% degradation after 50 cycles at a constant stack voltage.	ΔPower ≤ 0.1% degradation after 100 cycles at a constant stack voltage.
TEST SEQUENCE	1) Steady State Test - 1000 hours 2) Transient Test 3) Steady State Test - 500 hours	1) Steady State Test - 1000 hours 2) Transient Test 3) Steady State Test - 500 hours	1) Steady State Test – 1000 hours 2) Transient Test 3) Steady State Test - 500 hours
FUEL TYPE	For the complete duration of the Steady State and Transient Tests, operate the Prototype on either a commercial commodity, natural gas, gasoline, or diesel fuel (s) or a representative fuel based on respectively methane, iso-octane, or hexadecane corresponding to the proposed primary application (s). If multiple applications using different fuels are proposed split the total test time equally among the different fuel types.	For the complete duration of the Steady State and Transient Tests, operate the Prototype on either a commercial commodity natural gas, gasoline, or diesel fuel (s) corresponding to the proposed primary application (s). Utilize external or internal primary fuel reformation or oxidation. If multiple applications using different fuels are proposed split the total test time equally among the different fuel types.	For the complete duration of the Steady State and Transient Tests, operate the Prototype on either a commercial commodity natural gas, gasoline, or diesel fuel (s) corresponding to the proposed primary application (s). Utilize external or internal primary fuel reformation or oxidation. If multiple applications using different fuels are proposed split the total test time equally among the different fuel types.
MAINTENANCE INTERVALS	Design aspects should not require maintenance at intervals more frequent than 1000 operating hours.	Design aspects should not require maintenance at intervals more frequent than 1000 operating hours.	Design aspects should not require maintenance at intervals more frequent than 1000 operating hours.
DESIGN LIFETIME	≥ 40,000 operating hours for stationary applications and 5,000 hours for transportation applications for military uses.	≥ 40,000 operating hours for stationary applications and 5,000 hours for transportation applications for military uses.	≥ 40,000 operating hours for stationary applications and 5,000 hours for transportation applications for military uses.

THE CORNERSTONE OF THE ALLIANCE INTELLECTUAL PROPERTY

For SECA to be a true National Program, it was determined that the research and development work performed in the Core Technology Program supported with Federal funding must be available to all Industrial Team participants. In return, the Industrial Teams would help determine relevant research and development topics based on their design specific experience and needs. The DOE believes this arrangement remains advantageous to the intellectual property originator and also benefits U.S. National interests. The following were considerations leading to this structure:

- If Core Technology Program participants could exclusively license to anyone they chose, including outside of the SECA Industrial Teams, then it would be unlikely that Industrial Teams would be willing to collaboratively define the Core Technology Program objectives. Based on past fuel cell program experience, Industrial Teams in general would prefer to keep most development work in-house. This is not necessarily the best technical approach or best use of public funds since one company would typically not possess a concentration of the best talent, redundant equipment and facilities would have to be purchased, and redundant research and development efforts would have to be performed. This would negate the SECA goal of leveraging government funds to address the most difficult problems in an effort to accelerate commercialization of this nationally important technology.

- Making the intellectual property available to as many Industrial Teams as needed it, would ensure that the individual technology pieces were incorporated into the best designs versus that of only the highest bidder (not necessarily possessing the technology with the best chance for commercial deployment). This would benefit U.S. national interests.

- A market for intellectual property is being created. The Core Technology Program members will have an immediate set of potential licensees for their invention(s), and, if the Industrial Teams are successful in commercializing their fuel cell systems, will reap income in the form of royalties or other cash payments.

- By making the intellectual property available to the Industry Teams on a non-exclusive basis, the value of an individual license may be less but the cumulative value may very well be greater. If the intellectual property is important, all Industry Teams will need to have it to remain competitive.

- If the intellectual property were held by a small company, university, or a national laboratory that is unwilling to negotiate in good faith, that technology could be unavailable for an extended period of time. This intellectual property arrangement should prevent this from occurring. This would benefit U.S. national interests.

The basic terms of what is called an “exceptional circumstance” under the Bayh-Dole Act are intellectual property developed in the SECA Core Technology Program will be offered to all Industrial Teams as a non-exclusive license upon terms that are reasonable under the circumstances, including royalties. The field-of-use may be limited to solid oxide fuel cell applications with partially exclusive licensing permitted for other fields-of-use. The offer must be held open for at least one year after the U.S. patent issues and the invention owner must agree to negotiate in good faith. In the event the parties to the negotiation cannot reach agreement on the terms of the license within nine months of initiating good faith negotiations, the Industrial Team members shall have the right of a third party beneficiary to maintain an action in a court of competent jurisdiction to obtain a non-exclusive license on reasonable terms and conditions.

COST GOALS

Solid Oxide Fuel Cell Stack and Balance-of-Plant Cost for a 5 kW Modular Unit

The DOE has established $400/kW as a system factory cost goal for the SECA Program's SOFC module at the conclusion of the ten-year Program.

The following cost analysis is based on the compilation of material cost data from several independent sources and very generic designs. A 50% contingency has been included in the material evaluation to provide conservatism, account for unknowns, and for other small uncounted for costs.

The estimate is based on two standard sets of potential materials that tend to bound the possibilities. The DOE is aware that other possible material sets are currently under development. Manufacturing costs are somewhat more difficult to discuss although studies have also accounted for these. As a crude estimate, it is assumed that at large scale production levels using relatively simple manufacturing techniques, manufacturing will add 15 to 20 % additional cost to the stack.

Materials Cost

Material costs are based on a generic anode supported planar solid oxide fuel cell arrangement and a projected performance of the 0.6 W/cm^2 that has been demonstrated in a planar SOFC stack (Honeywell, Inc., (1)). The material costs are evaluated for both metallic (Table II) and ceramic (Table III) interconnects. The ceramic interconnect design is feasible in the near term. The metallic interconnect design requires further development of either a higher temperature metallic interconnect or lower temperature stack. Currently Pacific Northwest National Laboratory and Argonne National Laboratory are working on this as part of the SECA program. The other key assumption is that the cost of rare earth materials (primarily lanthanum and yttrium) can be obtained in bulk at a price factor of five less than for small quantities. Two industrial companies (one U.S. DOE fuel cell developer and an automotive supply company) have substantiated this assumption.

Table II. Material Costs with Metallic Interconnects

SOFC Components	Amount of material (g/100 cm^2)	Unit Cost ($/kg)	Material Cost ($/100 cm^2)	Material Cost (at 0.6 W/cm^2) ($/kW)
Stainless Steel (2.5 mm)	200	2	0.40	6.67
NiO/ZrO_2 (500 μm)	35	20	0.70	11.67
YSZ (10 μm)	1	24	0.024	0.40
$LaMnO_3$ (50 μm)	2.75	50	0.1375	2.30
End Plates (1.25cm, ss)				0.70
			50% contingency	10.87
			Total	$32.61

Table III. Material Costs with Ceramic Interconnects

Planar SOFC Components	Amount of material (g/100 cm^2)	Unit Cost ($/kg)	Material Cost ($/100 cm^2)	Material Cost (at 0.6 W/cm^2) ($/kW)
$LaCrO_3$ (2.5 mm)	165	50	8.25	137.50
NiO/ZrO_2 (500 μm)	35	20	0.70	11.67
YSZ (10 μm)	1	24	0.024	0.40
$LaMnO_3$ (50 μm)	2.75	50	0.1375	2.30
End Plates (1.25cm, ss)				0.70
			50% contingency	76.28
			Total	$228.85

System Costs

Arthur D. Little, Inc. (2) performed a conceptual design study of a nominal 5 kW SOFC system for five different cases. Table IV provides the basic system requirements considered and the results. The system flowsheet represented a relatively straightforward system. It can be seen that the lower bound of these cases indicates that the $400/kW cost goal is within reason.

The tabulated data reflects five scenarios representing both current and aggressive scenario's for SOFC performance. Stack power density has the most direct impact on capital cost. Another interesting result is the impact of the air inlet temperature which directly impacts efficiency due to the difference in excess air required for cooling but doesn't have a significant difference on capital cost. Sulfur content of 30 ppm versus 0 ppm also does not appear to have a large impact on capital cost.

Table IV, 5kW SOFC System Costs (2)

System Parameters					
	Base Case	Case 1	Case 2	Case 3	Case 4
Fuel	30 ppm sulfur gasoline	30 ppm sulfur gasoline	30 ppm sulfur gasoline	30 ppm sulfur gasoline	0 ppm sulfur diesel
Anode H_2 Utilization	90%	90%	70%	90%	90%
Single Cell Voltage	0.7	0.7	0.7	0.7	0.7
Power Density, W/cm^2	0.3	0.6	0.3	0.6	0.3
Cathode Inlet Air T, ° C	650	500	700	650	650
System Efficiency, %	37	40	26	37	37
System and Component Cost					
Stack					
• Electrode-Electrolyte Assembly	$217.6	$102.7	$253.6	$111.9	$218.4
• Stack balance of components	19.3	16.4	20.2	16.6	19.3
Fuel and Air Preparation					
• POX reformer (+ preheaters)	21.8	21.8	22.7	21.8	21.4
• Cathode Oxidizer (+ preheat & vaporizer	8.5	11.8	9.2	8.5	8.5
• ZnO bed	9.9	9.9	9.9	9.9	n/a
• Anode gas recuperator	12.4	12.1	14.8	12.4	n/a
• Eductor	2.4	2.4	2.4	2.4	2.4
• Secondary cathode air preheater	31.7	n/a	87.7	31.7	26.9
Rotating Equipment					
• Fuel Pump	21.8	21.8	21.8	21.8	21.8
• Air compressor and air filter	54.5	54.5	54.5	54.5	54.5
Balance of System					
• Insulation and channels	10.9	8.8	13.2	7.1	12.2
• Start-up and active cooling blower	15.7	15.7	15.7	15.7	15.7
• Controls and electrical	40.7	40.7	40.7	40.7	40.7
• Piping	17.0	17.0	17.0	17.0	17.0
Labor, indirect and depreciation	43.0	36.2	48.0	43.0	33.4
Total, $/kW	527	372	631	415	492

CONCLUSIONS

The U.S. Department of Energy's Solid State Conversion Alliance has been established to commercialize solid oxide fuel cell systems for low-cost, environmentally friendly power using a mass customization approach targeted at stationary, transportation, and corollary military applications. The Program has been initiated with the solicitation of the Industrial Teams and the Core Technology Program participants.

ACKNOWLEDGEMENTS

The authors would like to thank the many individuals at the U.S. DOE and Pacific Northwest National Laboratory who have worked to establish the SECA Program. The authors would also like to thank the many individuals and organizations who have labored over the years to bring the solid-oxide fuel cell technology to its current level of development and provided the foundation for this new nationally important Program. The authors would also like to thank Pacific Northwest National Laboratory and Argonne National Laboratory for background work essential to developing realistic SECA goals.

REFERENCES

(1) N. Minh, et. al., in *Solid Oxide Fuel Cells VI,* S. C. Singhal and M Dokiya, Editors, **PV 99-19**. p.68, The Electrochemical Society Proceedings Series, Pennington, NJ (1999).

(2) J. Thijssen, et.al.,*Conceptual Design of POX SOFC 5 kW net System,* Arthur D. Little, Inc. Report # 71316 (to be published), Cambridge MA (2000).